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THE MEASUREMENT OF CAPSULE HEAT TRANSFER GAPS USING NEUTRON RADIOGRAPHY

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ABSTRACT

The use of neutron radiographs to determine dimensional changes of heat transfer gaps in cylindrical nuclear fueled capsules is described. A method was developed which involves scanning a very fine grained neutron radiograph negative with a recording microdensitometer. The output of the densitometer is recorded on graph paper and the heat transfer gap is plotted as a well defined optical density change. Calibration of the recording microdensitometer ratio arms permits measurements to be made of the heat transfer optical density change from the microdensitometer trace. Total heat transfer gaps, measured by this method, agree with the physical measurements within ±0.005 cm.

E-6552

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SUMMARY

The use of neutron radiographs to determine dimensional changes of heat transfer gaps in cylindrical nuclear fueled capsules is described. A high resolution neutron radiograph of the nuclear fueled capsule was obtained utilizing a beam of thermal neutrons from the NASA, 60 megawatt, Plum Brook Reactor Facility. The neutron radiograph was scanned by a recording microdensitometer whose output was plotted on graph paper. The graphical representation of the light transmittance of the radiograph negative presented the heat transfer gap as a well defined optical density change, with a maximum at the inner wall of the containment can and a minimum at the outer wall of the clad fuel pin. A value was obtained for each increment on the graph paper by calibrating the microdensitometer ratio arms using precision scales. Linear measurements between the maximum and minimum density were made from the traces using a 7X optical comparator with a scale divided in 0.0127 cm increments.

Measurements using this technique agreed with physical measurements of the total heat transfer gap within ±0.005 cm over a range of gaps from 0.061 to 0.178 cm. This investigation was limited to less than 10 percent U-235 enriched uranium nitride fuel pellets in a hafnium-tungsten-tantalum alloy clad and sealed in a stainless steel can.

Instrumentation, such as stainless steel sheathed thermocouples, were found to interfere with the measurements described if they were routed through the heat transfer gap area as seen on the neutron radiograph.

INTRODUCTION

The development of space power reactor technology requires inspection of many irradiated nuclear fuel pins. Neutron radiography is finding increased application in this field, since it can pictorially show fuel swelling, cracking, and dimensional changes (refs. 1 to 4). These observations can be made during the course of irradiating experiments without specimen destruction.

Accurate measurements of cylindrical specimens are difficult to obtain (refs. 5 and 6) by radiography, since the variation in specimen thickness, across the diameter of the cylinder, causes a corresponding optical density variation in the radiograph negative. The nuclear fuel pins used in this study are constructed with a heat transfer gap between the clad nuclear fuel and the outer cylindrical container. Neutron

radiography was used in this investigation as a nondestructive method of observing and measuring the heat transfer gaps of nuclear fueled capsules during irradiation.

This report describes a technique for measuring heat transfer gaps from neutron radiographs. The method used involves scanning the radiograph negative with a recording microdensitometer to obtain a trace of the optical density variation across the diameter of the capsule. The optical density change representing the gap is measured from the microdensitometer trace and related to the physical measurement. Heat transfer gaps from 0.061 to 0.178 cm have been determined by this technique and agree with preassembly physical measurements to ±0.005 cm.

EXPERIMENTAL EQUIPMENT

The Plum Brook Reactor

The Plum Brook Reactor is operated by the National Aeronautics and Space Administration's Lewis Research Center at its Plum Brook Station in Sandusky, Ohio. The reactor is a pressurized, light water moderated, 60 megawatt test reactor. Figure 1 shows the reactor core, a 3 × 9 array of highly enriched uranium fuel elements, located approximately 6.5 meters below grade inside the reactor pressure tank. The fueled core is surrounded on four sides by a beryllium reflector, the south side containing a 4 × 8 element beryllium array for experimental usage.

The reactor pressure tank is enclosed in high density concrete and surrounded by four 8.2 meter deep quadrants, A, B, C, and D. Quadrants A, C, and D are normally filled with water for biological shielding. Quadrant B is normally dry with the reactor at power, shielding being provided by 2.7 meters of high density concrete. The neutron beam used for radiography is extracted from the west side of the south beryllium reflector section.

The Neutron Radiograph Facility

A sketch of the neutron radiograph facility, viewed south to north, is shown in figure 2. The major components of the facility are: (1) the ITA-1 thimble (neutron beam extraction tube), (2) the divergent neutron collimator (ref. 7), (3) the watertight sample holder at the rear of the collimator, and (4) the watertight foil cassette located inside of the sample holder.

The neutron beam is extracted from the core at ITA-1 by a 15.5 cm i.d. aluminum thimble 1.6 meters long. The thimble is bolted to a flanged penetration on the reactor pressure tank in quadrant A. The core end of the tube is within 1.27 cm of the west side of the reflector section and is closed by a flat aluminum plate. The quadrant end of the

thimble is sealed by an aluminum flange. Normally the thimble is filled with helium at 68 900 newton/meter^2 pressure during reactor power cycles. The thimble is flooded with water to provide biological shielding during reactor shutdown when the quadrant is drained.

The neutron collimator (fig. 3) is a 4.57 meter long, divergent type, aluminum collimator pressurized with helium to 68 900 newton/meter^2 to prevent distortion from the quadrant water pressure. The collimator entrance window is 2.54 cm square and 0.635 cm thick. The 0.953 cm thick exit window has a viewing area 7.62 by 76.2 cm. The collimation factor L/D is 180. The entrance window of the collimator butts flush against the ITA-1 thimble exit flange. Bolted to the rear of the collimator is a receiver which accepts and positions the sample holder for radiography.

The watertight sample holder (fig. 4) is a 12.2 by 12.2 by 115.57 cm box constructed of aluminum. The box has a 7.62 cm deep double bottom which is filled with lead shot for ballast. On the rear are four stainless steel leaf springs which hold the front face of the box tightly against the exit window of the collimator. In the hinged lid are a helium supply hose connection and two "acorn" head hold down bolts. A check valve is located on the rear of the box just above the ballast chamber. The check valve permits pressurization of the box and evacuation of water when radioactive specimens are being loaded underwater.

Guide rails on the side walls divide the box into two sections. The rear section, 2.86 cm deep, positions the cassette for each radiograph. The 8.57 cm deep front section is available for specimens to be radiographed.

The watertight cassette (fig. 5) is constructed of aluminum. The window in the cassette is 0.318 cm thick and has a 7.62 by 76.2 cm picture area. The cassette is loaded with a 0.013 cm thick indium convertor foil and two 0.102 cm thick cadmium backscatter shields.

THE RECORDING MICRODENSITOMETER

The density traces used for the heat transfer gap measurements were obtained with a Joyce-Loebl Mark III C double beam recording microdensitometer. The operation of this instrument is based on a true double beam light system in which two beams from a single light source are switched alternately to a single photomultiplier. If the two beams are of a different intensity a signal is produced by the photomultiplier, which, after amplification, causes a servomotor to move an optical attenuator so as to reduce the intensity difference to zero. In this way a continuously null balancing system is obtained in which the position of the optical attenuator is made to record the density at any particular part of a specimen.

Fueled Capsule Specimen

The fueled capsule used in this investigation was composed of a stack of seven annular pellets, five of stainless steel and two of partially enriched uranium nitride. The seven pellet array was completely enclosed in a hafnium-tungsten-tantalum alloy cladding and designated as the fueled pin. This fueled pin was sealed in a type 304L stainless steel containment can (fig. 6). The containment can inside diameter was machined larger in approximately one half of the can resulting in two different size heat transfer gaps in the completed capsule (fig. 7). Measurements were taken of the inside diameter of the stainless steel containment can and the outside of the fueled pin before assembly. The location of the measurements was identified by an orientation mark on the outside of the containment can. Measurements were also taken at 90^{o} from the orientation mark.

In the final experimental assembly, two fully instrumented capsules of this type are encased in a protective aluminum shield (fig. 8). This moved the capsule farther away from the convertor foil and also introduced 2.5 cm of aluminum between the capsule and the convertor foil. Measurements were also made from neutron radiographs of this configuration (fig. 9).

EXPERIMENTAL PROCEDURE

Characteristics of the Neutron Beam

The thermal neutron flux (neutrons with energies between 0.01 and 0.3 eV) available at the indium convertor foil varies with the control rod bank height throughout any reactor power cycle. Since the ITA-1 thimble is located in the upper west face of the core, the intensity of the neutron beam will increase throughout a power cycle as the control rods are withdrawn.

To be able to produce repeatable neutron radiographs, it is necessary to know the thermal neutron flux to within approximately 20 percent. Measurements of the radiograph beam at the image area have been made and the results are given in appendix A.

Optimization of the thermal neutron flux for radiographic contrast had yielded a value for the total thermal neutron fluence of 1×10^{11} N/cm^2, as determined from the thermal flux map, and this fluence was used in this investigation. Since it was known that the fluence value was high using the flux map (see appendix A) a gold foil determination was obtained for each of the four radiographs taken. The values obtained from the gold foils were between 4×10^{10} and 5×10^{10} N/cm^2.

Radiograph Procedure

The neutron radiographs were obtained by the transfer method (ref. 8). The cassette was loaded with a 0.0127 cm thick indium convertor foil, 7.62 cm wide by 30.5 cm long. The indium was placed against the neutron window in the bottom of the cassette cavity, with the center of the foil in the center of the cassette. Immediately behind the indium were placed two 0.102 cm thick, by 7.62 cm wide, by 76.2 cm long, cadmium backscatter shields. The aluminum backplate was then placed in the cassette cavity and the assembly was bolted together. A gold foil was taped to the front of the cassette at approximately the centerline of the neutron beam, and the cassette was loaded in the sample holder.

An aluminum plate, 0.213 cm thick, and sized to fit the specimen section of the sample holder, was used to mount the fueled capsule. The capsule was locked to the plate so that its centerline was 1.0 cm from the convertor foil and in the center of the 7.6 cm wide picture area. The capsule orientation mark was aligned with the neutron beam.

A spacer was placed in the specimen compartment of the sample holder. The mounted fueled capsule was inserted on top of the spacer placing it in the centerline of the divergent beam.

The lid to the sample holder was closed and sealed and the holder purged with helium. The sample holder was lowered into the quadrant water to a position directly above the receiver at the rear of the collimator. The sample holder was inserted into the receiver and exposure time was started when the sample holder was fully inserted. A small amount of helium was allowed to bubble out of the check valve in the sample holder throughout the exposure. Upon completion of the calculated exposure time the sample holder was withdrawn from the receiver, depressurized, and removed from the quadrant. The cassette was removed from the sample holder and the indium foil unloaded.

The indium foil was placed between two lead covered metal plates and taken to the photo lab. The foil was exposed to Kodak type AA X-ray film for two minutes. Following this exposure, the foil was placed between two pieces of Kodak, type R, single emulsion X-ray film, with the emulsion side to the foil. This layered package was placed in a standard X-ray medical cassette and allowed to decay for three hours. The type AA film was developed immediately and provided a check on specimen orientation. The type R film was used on all densitometric measurements. The time of decay of the foil between removal from the neutron beam and exposure to the type R X-ray film was 15 minutes.

Standard X-ray film development techniques were adhered to for all radiographs. The temperature of the solutions was maintained at 68° F. Developing time was 5 minutes, followed by 30 seconds in a stop-bath with agitation, and then 5 minutes in a fixer solution. The film was washed in 68° F running water for 20 minutes and dried in a film drier.

The procedure described was followed to obtain a radiograph of the

fueled capsule with the orientation mark 90° to the beam. The fueled capsule was then placed in the aluminum protective shield and a radiograph taken at both the 0° and 90° orientation.

Microdensitometer Calibration

Calibration of the microdensitometer was accomplished by scanning a 1.705 cm comparator scale divided into 0.013 cm increments, using a scanning slit 5×10^{-4} meters long and 2.5×10^{-5} meters wide and the 10:1 ratio arm. The 50:1 ratio arm was calibrated using a 0.003 cm metallized grating in a 5.08 cm square glass slide. Typical calibration traces are shown in figures 10 and 11.

Microdensitometer Analysis of Radiographs

Each of the radiographs of the capsule was analyzed using the recording microdensitometer. Traces were taken across the diameter of the capsule at approximately the centerline of the top fuel pellet, the third pellet from the top, and the bottom fuel pellet. The 5×10^{-4} meter long and 2.5×10^{-5} meter wide scanning slit was used. The film being measured was placed on the traveling stage of the microdensitometer which was connected by a 10:1 ratio arm to another table on which a pen recorder made a record of the optical density. Measurements were also made using a 50:1 ratio arm. Figure 12 is a typical microdensitometer trace across a fueled capsule with a heat transfer gap, using a 10:1 ratio arm. Figure 13 is a typical microdensitometer trace of just the heat transfer gap using a 50:1 ratio arm.

In figures 12 and 13, the distance between the maximum and minimum of the optical density change is shown as the heat transfer gap. Results of an investigation at this facility had shown that this optical density change was the heat transfer gap as seen by the neutron radiograph. In that investigation a larger diameter capsule, constructed of the same materials as the capsule in this study, was used. A small hole was drilled in the top of the outer containment can, and the heat transfer gap was partially filled with a neutron poison (gadolinium nitrate). A neutron radiograph was taken and microdensitometer traces obtained across the diameter of the capsule in the poisoned and nonpoisoned areas of the gap. An overlay of the traces showed that the maximum of the optical density change corresponded to the inner wall of the containment can as seen on the neutron radiograph.

The shape of the optical density change representing the heat transfer gap can be seen in the microdensitometer calibration curves which are basically the same. The rounding of the heat transfer gap optical density change is due to the cylindrical shape of the fueled capsule.

EXPERIMENTAL RESULTS AND DISCUSSION

The calibration of the 10:1 ratio arm of the microdensitometer gave a value of 0.025 cm for each 0.254 cm on the graph paper.

The calibration of the 50:1 ratio arm of the microdensitometer gave a value of 0.005 cm for each 0.254 cm on the graph paper.

The results of the recorder trace measurements and physical measurements of the heat transfer gaps are given in table I. Agreement in Case I is within ±0.005 cm in all measurements except that of the third pellet from the top in the 90° orientation. Since the densitometer trace across the same pellet in the 0° radiograph agreed with the physical measurement, and the physical measurements in this larger gap area varied as much as 0.0048 cm, it was felt that this was not a significant discrepancy.

This was confirmed by the table II measurements of the heat transfer gap. In all instances in this case the microdensitometer measurements agreed with the physical measurements within 0.005 cm. Table II measurements also showed that the resolution of the neutron radiograph facility is not affected by the aluminum shield around the fueled capsule or the displacement of the capsule from the convertor foil.

CONCLUDING REMARKS

The method described is capable of measuring total heat transfer gaps to within ±0.005 cm as demonstrated by agreement with preassembly physical measurements. Heat transfer gap measurements from neutron radiographs also have the advantage of yielding two sides of the gap which is beneficial in determining localized swelling. It would be well to note that the accuracy quoted here may only be applicable to neutron radiographs taken at this facility. The resolution and accuracy of a neutron radiograph are dependent on the collimation of the thermal neutron beam.

At the present time this method is being used at this facility to monitor heat transfer gap changes in some twenty fueled capsule similar in construction to the dummy used. All of these capsules have a range of heat transfer gaps from 0.061 to 0.178 cm. Determinations of heat transfer gaps larger or smaller than these have not been fully investigated. It is probable that at some gap size larger than those investigated, the divergence of the neutron beam will indicate a larger gap as measured from the neutron radiograph. Small gaps will yield a small optical density change and at some gap dimension accurate measurements will not be possible due to the resolution of the collimated thermal neutron beam.

The method described is applicable to capsules of other construction. However, since other materials could cause scattering of the neutron beam

or introduce factors which could decrease the accuracy of the measurements, calibration runs would be necessary to establish limits on accuracy.

It has been observed that thermocouples sheathed in stainless steel, if routed through the heat transfer gap, will give erroneous measurements. However, thermocouples can be seen on the radiograph. Normally the entire gap is not obscured so that the actual gap measurement can still be determined.

APPENDIX - NEUTRON AND GAMMA MAP OF NEUTRON RADIOGRAPH FACILITY - OCTOBER 1969

Thermal and epithermal neutron fluxes, gamma dose rates, and gold and cobalt cadmium ratios were determined at bank heights from 50 cm to about 71 cm. The results of the thermal flux measurements are shown in figures 14 and 15. The gamma dose rate, at two bank heights, is plotted in figure 16. The measured epithermal fluxes are noted in table III. The cadmium ratios were found to be 19.7 for gold and 47.3 for cobalt.

The normal dosimetry, gold wires, lithium fluoride microrods, indium, sulfur, nickel, magnesium, aluminum, and cobalt were used to obtain the measurements. They were positioned in the sample holder in the cassette area where the indium convertor foil would be located. Cadmium backscatter shields were not used behind the dosimetry. Since the image area of the radiographic facility is surrounded by water which acts as an isotropic scattering plane for thermal neutrons, all of the measured values for the thermal neutron flux were higher than the actual beam thermal neutron flux.

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TABLE I. - DETERMINATIONS OF CAPSULE HEAT TRANSFER GAPS FROM NEUTRON RADIOGRAPHS

Case I. - Fueled capsule.							
Neutron radiograph number	Capsule orientation	Trace location	Lever ratio	Left gap, cm	Right gap, cm	Total gap, cm	Physical measurements i.d. SS - o.d. fuel, cm
276	90°	Top fuel pellet	10:1	0.041	0.048	0.089	0.0912
			50:1	.043	.051	.094	.0912
		Third pellet from top	10:1	0.043	0.041	0.084	0.0907
			50:1	.043	.041	.084	.0907
		Bottom fuel pellet	10:1	0.033	0.028	0.061	0.0602
			50:1	.030	.030	.061	.0602
277	0°	Top fuel pellet	10:1	0.046	0.048	0.094	0.0945
			50:1	.043	.051	.094	.0945
		Third pellet from top	10:1	0.043	0.048	0.091	0.0930
			50:1	.046	.046	.092	.0930
		Bottom fuel pellet	10:1	0.033	0.033	0.066	0.0592
			50:1	.030	.033	.063	.0592

TABLE II. - DETERMINATIONS OF CAPSULE HEAT TRANSFER GAPS FROM NEUTRON RADIOGRAPHS

Case II. - Fueled capsule in aluminum shield.							
Neutron radiograph number	Capsule orientation	Trace location	Lever ratio	Left gap, cm	Right gap, cm	Total gap, cm	Physical measurements i.d. SS - o.d. fuel, cm
278	90°	Top fuel pellet	10:1	0.043	0.048	0.091	0.0912
			50:1	.043	.046	.089	.0912
		Third pellet from top	10:1	0.043	0.051	0.094	0.0907
			50:1	.043	.051	.094	.0907
		Bottom fuel pellet	10:1	0.028	0.030	0.058	0.0602
			50:1	.030	.033	.063	.0602
279	0°	Top fuel pellet	10:1	0.046	0.046	0.092	0.0945
			50:1	.046	.046	.092	.0945
		Third pellet from top	10:1	0.051	0.048	0.099	0.0930
			50:1	.048	.048	.096	.0930
		Bottom fuel pellet	10:1	0.030	0.033	0.063	0.0592
			50:1	.030	.033	.063	.0592

TABLE III. - EPITHERMAL FLUX

Position and bank height	Flux, neutrons/cm^2-sec-eV/60 MW		
	1.46 eV	4.9 eV	330 eV
+25.4 cm, 49.8 cm	1.29×10^5	4.46×10^4	4.75×10^2
+12.7 cm, 49.8 cm	7.81×10^5	2.64×10^5	2.63×10^3
+0 cm, 49.8 cm	9.07×10^5	2.82×10^5	2.93×10^3
-12.7 cm, 49.8 cm	6.86×10^5	2.12×10^5	2.21×10^3
+25.4 cm, 49.8 cm	3.51×10^5	9.89×10^4	1.07×10^3
+0 cm, 67.6 cm	1.43×10^6	4.78×10^5	2.98×10^3

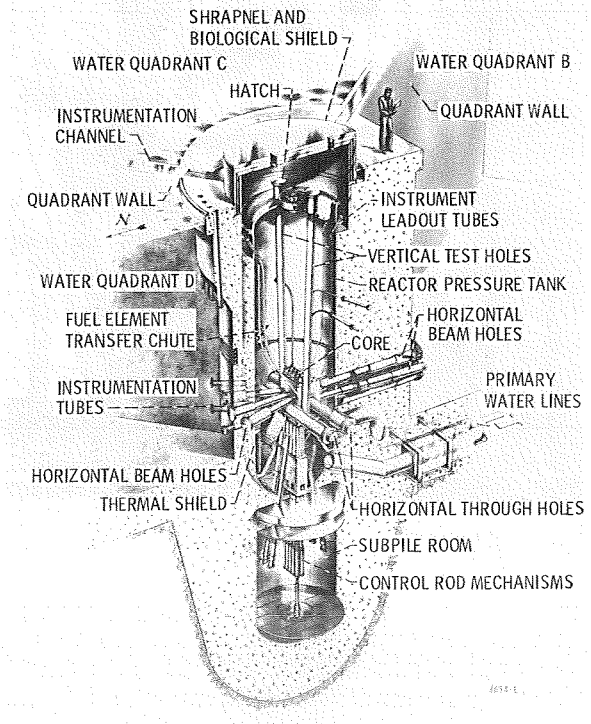

Figure 1. - Cutaway perspective drawing of reactor tank assembly.

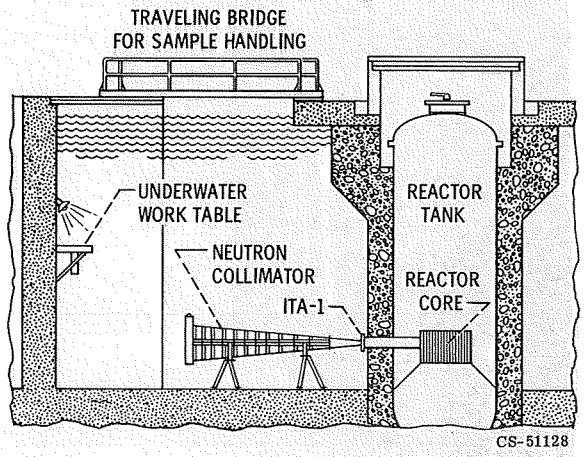

Figure 2. - The Plum Brook reactor neutron radiograph facility.

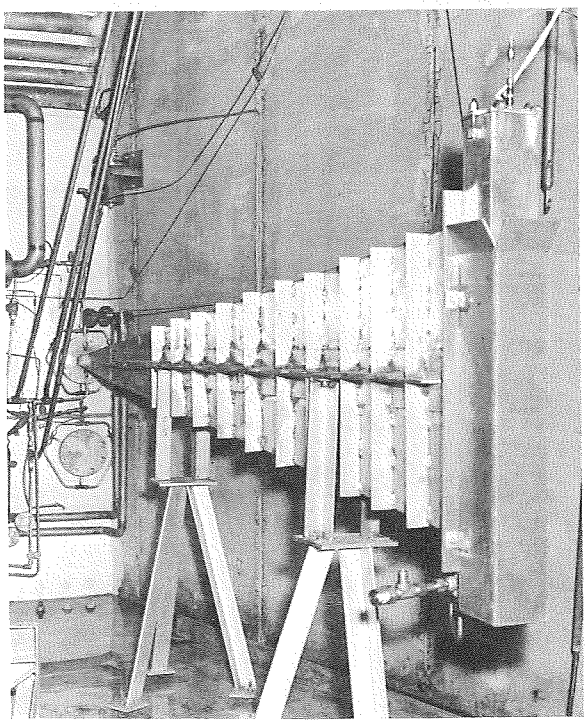

Figure 3. - The 4.57 meter divergent neutron collimator is shown here butted to the ITA-1 thimble. The water tight sample holder is positioned in the receiver.

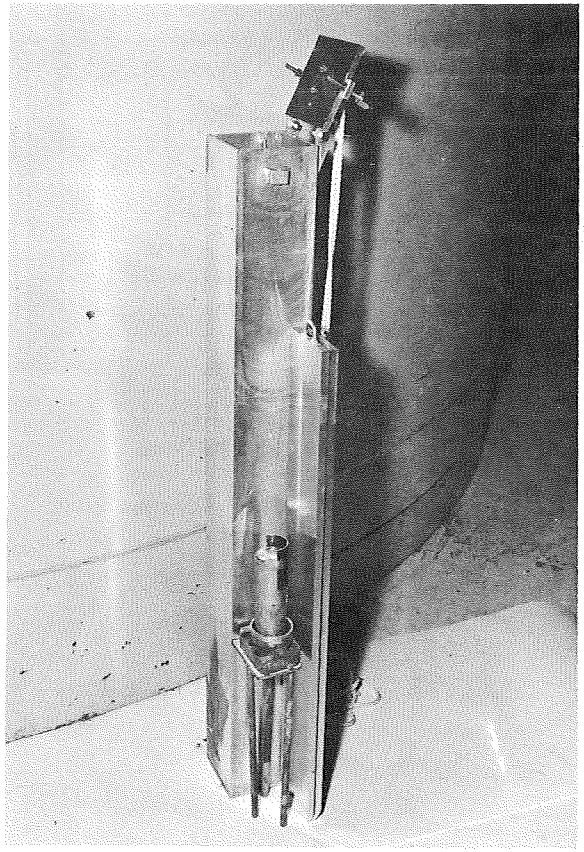

Figure 4. - The watertight specimen holder, loaded cassette and a specimen mounted on a spacer.

Figure 5. - The watertight cassette being loaded.

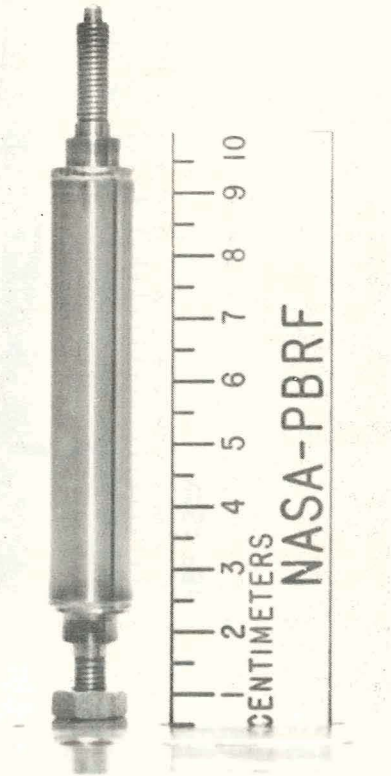

Figure 6. - An experimental fueled capsule.

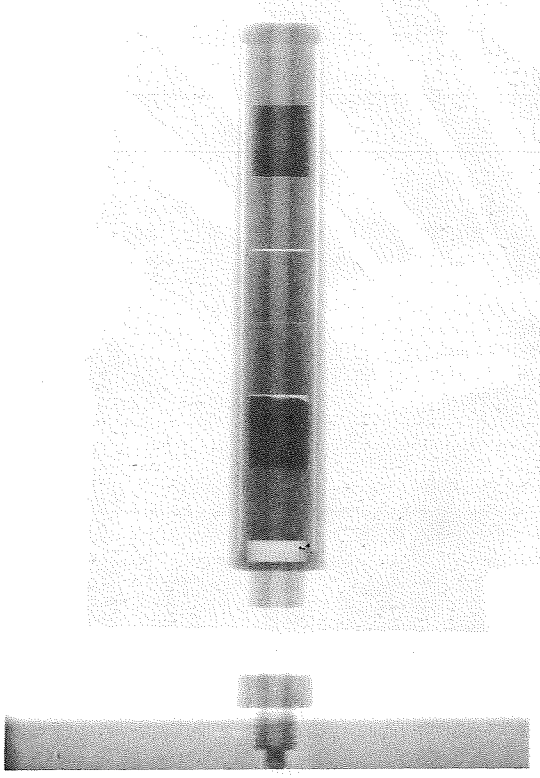

Figure 7. - A neutron radiograph of the experimental capsule. The dark pellets are enriched uranium nitride, the lighter pellets are stainless steel.

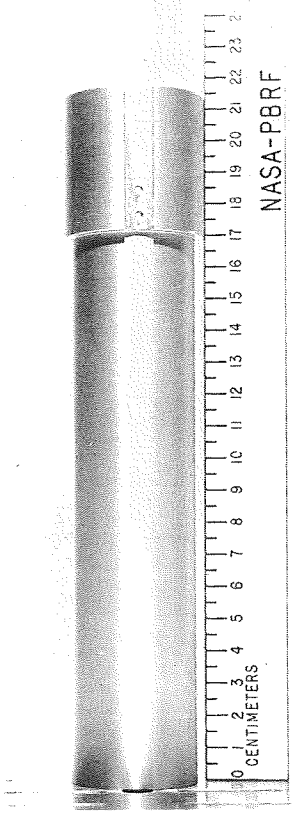

Figure 8. - Aluminum protective shield.

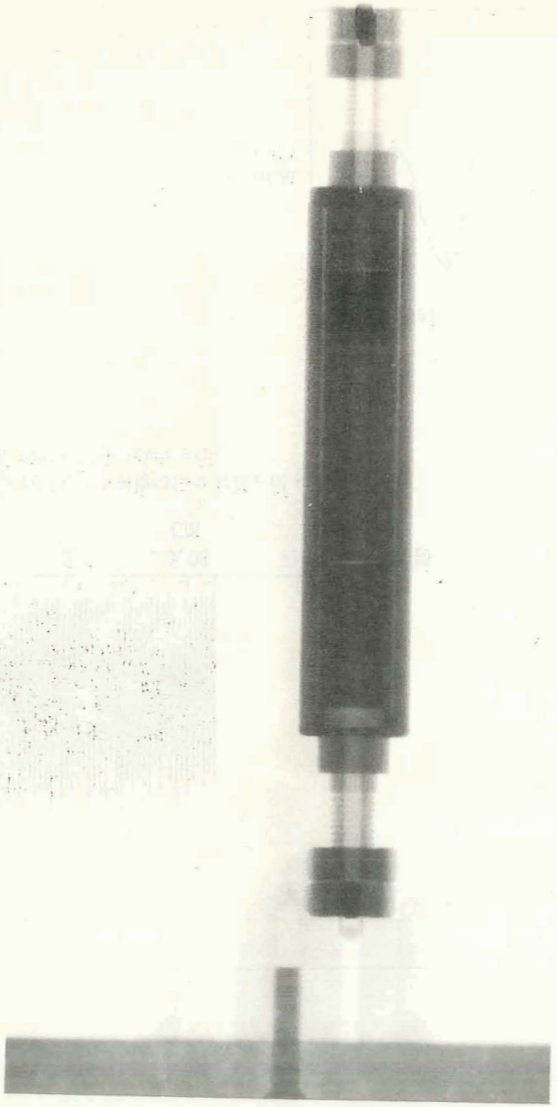

Figure 9. - A neutron radiograph of the fueled capsule in the protective aluminum shield.

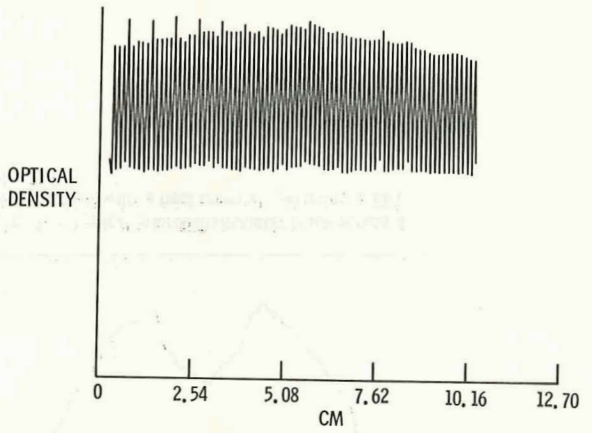

Figure 10. - Calibration trace of microdensitometer 10:1 ratio arm.

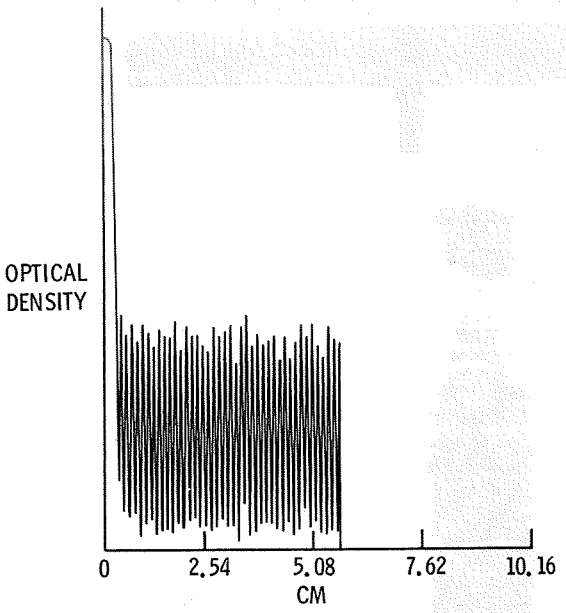

Figure 11. - Calibration trace of microdensitometer 50:1 lever arm.

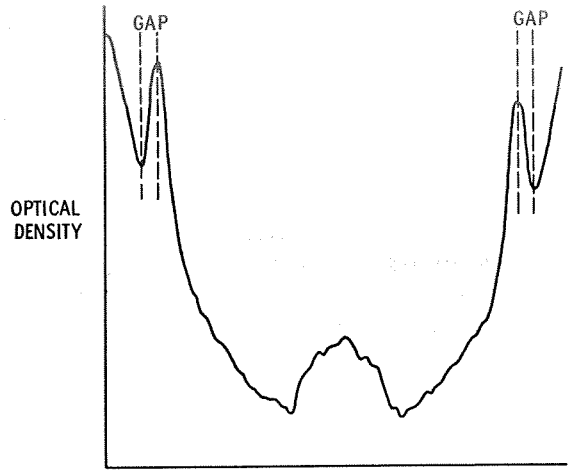

Figure 12. - Typical microdensitometer trace across a fueled capsule with a heat transfer gap using a 10:1 ratio arm.

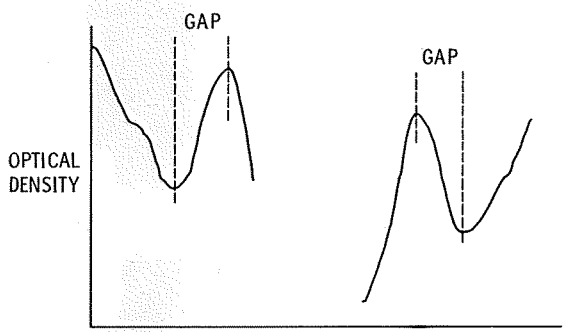

Figure 13. - Typical microdensitometer traces of the heat transfer gap using a 50:1 ratio arm.

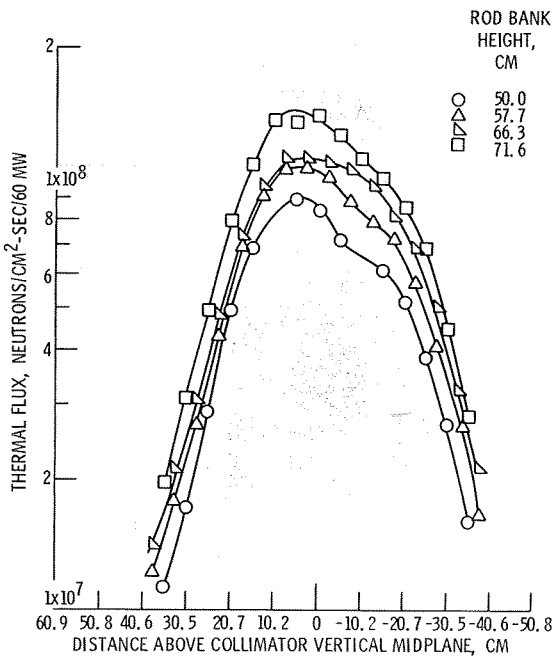

Figure 14. - Neutron radiograph facility thermal flux vertical traverse.

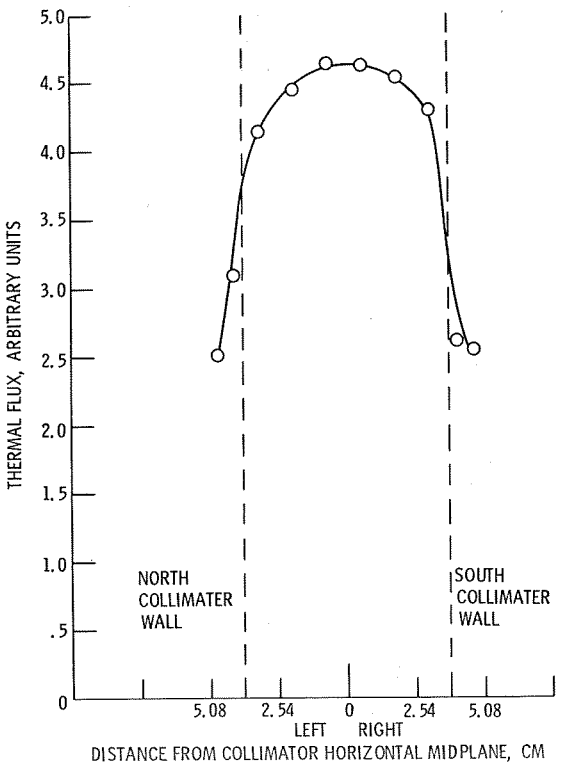

Figure 15. - NRF thermal flux horizontal traverse data on vertical midplane, 57.7 cm rod bank height. Left-right orientation is facing beam origin.

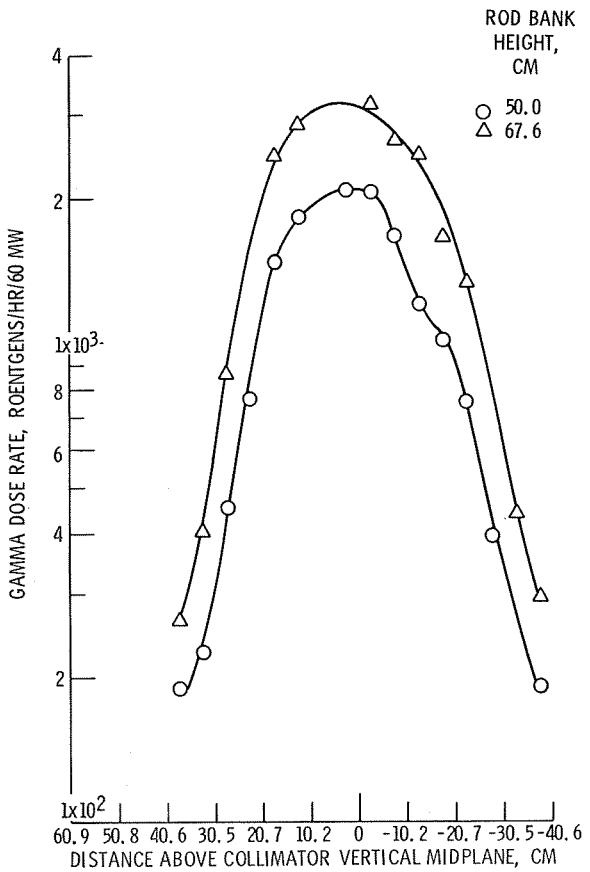

Figure 16. - Neutron radiograph facility gamma dose rate vertical traverse.